CERN-TH.7443/94
UM-TH-94-34
hep-ph/9409310

NEW NEUTRAL GAUGE BOSONS AND NEW HEAVY FERMIONS IN THE LIGHT OF THE NEW LEP DATA

Enrico Nardi[a,†], Esteban Roulet [b] and Daniele Tommasini [b]

[a] *Randall Laboratory of Physics, University of Michigan*
Ann Arbor, MI 48109–1120, U.S.A.

[b] *Theory Division, CERN, CH-1211, Geneva 23, Switzerland*

Abstract

We derive limits on a class of new physics effects that are naturally present in grand unified theories based on extended gauge groups, and in particular in E_6 and $SO(10)$ models. We concentrate on *i*) the effects of the mixing of new neutral gauge bosons with the standard Z_0; *ii*) the effects of a mixing of the known fermions with new heavy states. We perform a global analysis including all the LEP data on the Z decay widths and asymmetries collected until 1993, the SLC measurement of the left–right asymmetry, the measurement of the W boson mass, various charged current constraints, and the low energy neutral current experiments. We use a top mass value in the range announced by CDF. We derive limits on the Z_0–Z_1 mixing, which are always $\lesssim 0.01$ and are at the level of a few *per mille* if some specific model is assumed. Model-dependent theoretical relations between the mixing and the mass of the new gauge boson in most cases require $M_{Z'} > 1\,\mathrm{TeV}$. Limits on light–heavy fermion mixings are also largely improved with respect to previous analyses, and are particularly relevant for a class of models that we discuss.

Revised version (november 1994), to appear in Phys. Lett. B

† Address from November 1994 : *Department of Particle Physics, Weizmann Institute of Science,* P.O.B. 26, Rehovot, 76100 Israel.
E-mail addresses:

nardi@wiswic.weizmann.ac.il, roulet@vxcern.cern.ch,tommasini@vxcern.cern.ch

CERN-TH.7443/94
UM-TH-94-34
September 1994

1 Introduction

The sensitivity of LEP experiments to the direct production of new particles has not increased significantly with respect to that achieved after the first-year runs. However, the accumulation of large statistics and the improvements on the systematics now allows not only to test with much more detail the predictions and consistency of the standard model (SM), including the virtual effects of the top quark and Higgs boson, but also to improve considerably the ability to search for (or constrain) some subtle indirect manifestations of new physics beyond the SM.

Among these last ones, the implications of the combined LEP measurements up to 1993 are of particular importance for new neutral gauge bosons that could mix with the standard Z_0 (so that the Z boson mass eigenstate has a small component with non-standard couplings) and also for heavy fermions mixed with the known ones. In fact if the new fermions have non-canonical $SU(2) \times U(1)$ quantum numbers (e.g. left-handed singlets or right-handed doublets) they modify the couplings of the electroweak gauge bosons with the light particles.

These new kinds of physics are a common feature of many GUT theories, such as $SO(10)$ and E_6. The search for the tiny effects mentioned above then allows us to look indirectly for the new states predicted by these models, even if their direct production is unaccessible at the energies achievable with present colliders. Global constraints on these effects have been regularly performed in the past using the available electroweak data, [1]–[5]. In this paper we show that the inclusion of LEP and SLC data up to 1993 allows a significant improvement of the constraints on the deviations of the fermion couplings with respect to their SM values and hence strengthen the bounds on the above-mentioned mixings, in some cases even by an order of magnitude. The value of the top quark mass recently announced by the CDF collaboration [6], $m_t = 174 \pm 10^{+13}_{-12}$, is also relevant for this analysis, since some bounds (such as those on Z_0 mixing with an additional gauge boson or those on the mixing of the b quark) are correlated with it.

Finally we briefly discuss whether it is possible that new physics effects of the kind discussed here could account for the deviation from the SM expectations of some measurements, such as Γ_b^{LEP}, A_{LR}^{SLC} and A_τ^{FB}. We can anticipate that we find essentially negative results.

2 Z_0–Z_1 mixing

The formalism describing the mixing of the standard neutral Z_0 boson of the electroweak gauge group $\mathcal{G}_{SM} = SU(2) \times U(1)$ with a new Z_1 associated with an extra $U'(1)$ factor has been discussed at length in the past [4, 5]. Here we just recall a few relevant points.

In order to span a wide range of Z' models, we will as usual take the $U'(1)$ as a combination of the two additional Abelian factors in the decomposition $E_6 \to SO(10) \times$

$U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi$, where $\mathcal{G}_{SM}$ is assumed to be embedded in the $SU(5)$ factor. We hence parametrize the new gauge boson as

$$Z_1 = s_\beta Z_\psi + c_\beta Z_\chi, \tag{1}$$

where $s_\beta \equiv \sin\beta$, $c_\beta \equiv \cos\beta$. We will present results for the most commonly considered χ, ψ and η models, corresponding respectively to $s_\beta = 0$, 1 and $-\sqrt{5/8}$.

A mixing between Z_0 and Z_1 leads us to the two mass eigenstates

$$\begin{pmatrix} Z \\ Z' \end{pmatrix} = \begin{pmatrix} c_\phi & s_\phi \\ -s_\phi & c_\phi \end{pmatrix} \begin{pmatrix} Z_0 \\ Z_1 \end{pmatrix}. \tag{2}$$

Although one may consider ϕ as being a free parameter, one should remember that in any given model one generally has $\phi \simeq C M_Z^2/M_{Z'}^2$, where $C \sim O(1)$ is fixed once the vacuum expectation values (VEVs) of the Higgs fields giving masses to the gauge bosons are specified. This theoretical relation between $M_{Z'}$ and ϕ has the important implication that the very stringent constraints on the mixing angle ϕ obtained by LEP at the Z-pole (see below) induce, once a model fixing C is assumed, an indirect bound on $M_{Z'}$ typically much stronger ($M_{Z'} \gtrsim$ 1 TeV) than those arising from direct Z' searches at the Tevatron ($M_{Z'} \gtrsim 450$ GeV for 25 pb^{-1} of integrated luminosity [8]) or those resulting from the effects of Z' exchange on low-energy neutral current experiments ($M_{Z'} \geq 200-300$ GeV) [4, 5, 8]. In view of these bounds we will neglect in the following Z' exchange and Z–Z' interference effects in the neutral current (NC) processes, and we will only consider the modifications of the Z couplings to fermions induced by the small admixture with the Z_1.

Due to the Z_0–Z_1 mixing, the vector and axial-vector fermion couplings appearing in the NC $J_Z^\mu = \bar{\Psi}^f (v^f + a^f\gamma_5)\gamma_\mu \Psi^f$, which couples to the physical Z boson, read[1]

$$\begin{aligned} v^f &= c_\phi v_0^f + s_\phi s_W v_1^f, & (3)\\ a^f &= -s_\phi a_0^f + c_\phi s_W a_1^f. & (4) \end{aligned}$$

Within the SM, and including radiative corrections, one has

$$v_0^f = \sqrt{\rho_f}\,[t_3(f_L) - 2\,Q^f \sin^2\theta_{eff}^f] \quad , \quad a_0^f = \sqrt{\rho_f}\, t_3(f_L), \tag{5}$$

where $\sin^2\theta_{eff}^f$ and the ρ_f factors have been evaluated by means of the ZFITTER code[2] [7], as functions of the input parameters m_t, $\alpha_s(M_Z)$ and m_H. The Z_1 couplings v_1 and a_1 depend on the assumed $U'(1)$ model (i.e. on s_β) and can be found in refs. [4, 5]. The effects of the SM radiative correction induced by the mixings with the new particles, as well as the radiative effects of new physics, are expected to be small and have been neglected. A more detailed justification of this assumption can be found in [4].

Since we are neglecting Z' propagator effects, the only quantity in which the Z' mass appears explicitly is $\rho_{mix} = 1 + (M_{Z'}^2/M_Z^2 - 1)s_\phi^2$. This term affects the $SU(2)$ gauge coupling deduced using as numerical inputs G_F, α and the value of M_Z measured at LEP, thus modifying both the overall strengths ρ_f and the $\sin^2\theta_{eff}^f$ factors. Since the effects

[1] The sine of the weak mixing angle s_W appears due to the normalization of the $U'(1)$ coupling [4].

[2] We thank D. Bardin for providing us with the 1994 updated version of the program.

of ρ_{mix} in the LEP observables are crucial to constrain the mixing ϕ, the limits on the Z_0–Z_1 mixture will depend on the Z' mass, generally improving with larger $M_{Z'}$ values.

A second remark is that ρ_{mix} enters as a multiplicative factor in the effective ρ parameter. Then the combined appearance of $\rho_{mix} \cdot \rho_{top}$, with $\rho_{top} \simeq 1 + \frac{3G_F m_t^2}{8\sqrt{2}\pi^2}$, induces a strong correlation between the gauge boson mixing and the top mass. Hence the top mass measurement by CDF [6] turns out to be relevant to establish precise bounds on the mixing angle ϕ.

3 Fermion mixing

A mixture of the known fermions with new heavy states can in general induce both flavour changing (FC) and non-universal flavour diagonal vertices among the light states. The first ones are severely constrained (for most of the charged fermions) by the limits on rare processes [9]. Here we aim to constrain the second ones by means of the large set of precise electroweak data.

Due to the extremely tight constraints on the FC mixings [9], neglecting them will not affect our numerical analysis on the flavour diagonal ones, since in general the limits on the latter ones turn out to be larger by some orders of magnitude. From a theoretical point of view, the absence of FC parameters in the formalism that we will outline here is equivalent to the assumption that different light mass eigenstates have no mixtures with the same new state [1].

The couplings of the light charged fermions can then be described with just two parameters for each flavour: $(s^f_\alpha)^2 \equiv \sin^2\theta^f_\alpha$, $\alpha = L, R$, which account for the mixing with exotic states (i.e. having non-canonical $SU(2)\times U(1)$ quantum numbers) of each of the two fermion chiralities. Since the mixing always involves states of equal electric charges, only the piece proportional to the weak isospin $t_3(f)$ in (5) is affected by the fermionic mixing. In particular, the chiral couplings $\epsilon^f_{L,R} = (v^f \pm a^f)/2$ are modified according to (see eq. 2.15 of ref. [4])

$$\epsilon^f_\alpha = t_3(f_\alpha) - Q^f \sin^2\theta^f_{eff} + \left[t_3(f^{\mathcal{N}}_\alpha) - t_3(f_\alpha)\right](s^f_\alpha)^2 \quad , \; \alpha = L, R \quad , \tag{6}$$

where $t_3(f^{\mathcal{N}}_\alpha)$ is the isospin of the new state $f^{\mathcal{N}}$ that mixes with the known state f. (For notational simplicity we omit hereafter the $\sqrt{\rho_f}$ factors in the expressions for the couplings.) Eq. (6) shows that when a doublet state is mixed with a singlet, the isospin-dependent part of the coupling is reduced by a factor $(c^f_L)^2$, while the mixing of a singlet $(t_3(f_R) = 0)$ with a new exotic doublet $(t_3(f^{\mathcal{N}}_R) = \pm 1/2)$ induces a coupling proportional to $t_3(f^{\mathcal{N}}_R)(s^f_R)^2$. Clearly, a mixing between states of the same isospin does not affect the overall electroweak couplings. Here we will only consider mixings with new states that are either exotic singlets or exotic doublets, i.e. $t_3(f^{\mathcal{N}}_L) = t_3(f_R) = 0$ and $t_3(f^{\mathcal{N}}_R) = t_3(f_L) = \pm 1/2$. Then, in the absence of extra new gauge bosons, we have

$$v^f = t_3(f_L)[1 - (s^f_L)^2 + (s^f_R)^2] - 2Q^f \sin^2\theta^f_{eff} \tag{7}$$

$$a^f = t_3(f_L)[1 - (s^f_L)^2 - (s^f_R)^2]. \tag{8}$$

The mixing among the neutral fermionic states is not so simple, both because of the lack of strong evidence against FCNC among neutrinos and because of the possible existence

of more than one type of exotic states (singlets, exotic doublets with $t_3(N_L) = -1/2$, etc. [1, 10]). However, after summing over the undetected final neutrinos and neglecting $O(s^4)$ terms, the different NC observables can be obtained by replacing the neutrino couplings in the SM expressions by effective couplings, which depend on just one mixing angle for each flavour:

$$v_{\nu_i} = a_{\nu_i} = \frac{1}{2} - \frac{\Lambda_i}{4}(s_L^{\nu_i})^2. \tag{9}$$

The additional parameter Λ describes the type of state involved in the mixing and, for instance, for a mixing with new ordinary, singlet or exotic doublet neutrinos we have $\Lambda = 0$, 2 or 4 respectively.

An important indirect effect of the presence of new fermions is to alter the prediction for μ decay, in such a way that the effective μ-decay constant $G_\mu = 1.16637(2) \times 10^{-5}$ GeV^{-2} is related to the fundamental coupling G_F through the fermion mixing angles [1, 2],

$$G_\mu = G_F c_L^e c_L^\mu c_L^{\nu_e} c_L^{\nu_\mu}. \tag{10}$$

As a consequence, all the observables that depend on the strength of the weak interactions G_F are affected by the mixing angles θ_L^e, θ_L^μ, $\theta_L^{\nu_e}$ and $\theta_L^{\nu_\mu}$. This is the case, for instance, for the W boson mass, for the effective couplings of the fermions with the Z boson, and for the Cabibbo–Kobayashi–Maskawa (CKM) matrix elements [1, 2].

The complete formalism describing fermion mixings and also the simultaneous presence of Z_0–Z_1 mixing is given in ref. [4].

4 Theoretical expectations for the fermion mixings

As regards the theoretical expectations for the mixing of the known fermions with new heavy states, there is no exact model-independent relation between the masses of the heavy partners and the corresponding mixings. However, in the framework of some classes of models, it is still possible to make some general statements and/or work out some order-of-magnitude estimates for the mixings.

For the charged states, the L (or R) mixing angles result from the diagonalization of the $N \times N$ symmetric squared mass matrix for the known and the new states $\mathcal{M}\mathcal{M}^\dagger$ (or $\mathcal{M}^\dagger\mathcal{M}$). We know that the relevant eigenvalues must satisfy the hierarchy $m^2_{\rm light} \ll m^2_{\rm heavy}$ (with $m_{\rm heavy} \gtrsim 100$ GeV), and we can outline two main mechanisms that would naturally produce such a pattern for the light and heavy masses.

a) See-saw models

In these models the general form of the squared mass matrix is

$$\mathcal{M}\mathcal{M}^\dagger \sim \begin{pmatrix} \delta^2 & d^2 \\ d^2 & \sigma^2 \end{pmatrix}, \tag{11}$$

with $\delta,\ d \ll \sigma$. If $\delta \sim d$, as is the case if both these entries are generated by VEVs of standard Higgs doublets, we expect for the mass eigenvalues $m_{\rm light} \sim \delta$, $m_{\rm heavy} \sim \sigma$, and $s_{L,R} \sim d^2/\sigma^2 \sim m^2_{\rm light}/m^2_{\rm heavy}$. A different scenario appears when $\delta \lesssim d^2/\sigma$, for which $m_{\rm light} \sim d^2/\sigma$, $m_{\rm heavy} \sim \sigma$, and $s_{L,R} \sim d^2/\sigma^2 \sim m_{\rm light}/m_{\rm heavy}$. Assuming $m_{\rm heavy} \gtrsim 100\,$GeV, we see that in the Dirac see-saw case the expectations for the mixings

are quite small. In the most favourable case of the bottom quark mixing, it can be as large as $(s^b_{L,R})^2 \sim 2 \times 10^{-3}$, which turns out to be at the limit of the present experimental sensitivity.

b) Quasi-degenerate mass matrices

It can happen that, as a consequence of some symmetries, in first approximation the light–heavy fermion mass matrices are degenerate. This implies that even if all the entries in the mass matrices are large, some states (corresponding to the light fermions) are massless, and would acquire tiny masses due to small flavour-dependent perturbations. To give a simple example of this mechanism, let us introduce a vector-like singlet of new fermions F_L and F_R, of the same charge and colour quantum numbers as those of the f_L component of a standard electroweak doublet, and of the corresponding electroweak singlet f_R. The general mass term reads

$$\mathcal{L}_{mass} = \lambda_0 \overline{F_L} F_R S + \lambda_1 \overline{F_L} f_R S + \gamma_0 \overline{f_L} F_R D + \gamma_1 \overline{f_L} f_R D, \tag{12}$$

where S and D are respectively a singlet and a doublet VEV. Let us also assume that because of some symmetries, in first approximation $\lambda_0 \simeq \lambda_1$ and $\gamma_0 \simeq \gamma_1$, and let us absorb these Yukawas in the D and S VEVs. Then, the light–heavy mass matrix squared that determines the ordinary–exotic L mixing angle reads

$$\mathcal{M}\mathcal{M}^\dagger \sim 2 \begin{pmatrix} D^2 & DS \\ DS & S^2 \end{pmatrix}, \tag{13}$$

and is clearly degenerate, implying $m_{\rm light} \simeq 0$ up to perturbations. At the same time, the ordinary–exotic L mixings are expected to be large, and could even be close to maximal. The expectations for the neutral sector were described in [10], where it was shown that a similar mechanism can also generate large light–heavy mixings even for massless neutrinos.

Clearly, in contrast to the see-saw case, models of this kind can be effectively constrained by analysing the most precise electroweak data, and in fact the tight bounds that we will derive for some mixings tend to disfavour this mechanism for the generation of the known fermion masses.

5 Experimental constraints

Within the SM, the precise electroweak experiments allow to constrain the values of the input parameters m_t, $\alpha_s(M_Z)$ and m_H, and an overall satisfactory agreement is found whith the predictions for a heavy top mass [17], compatible with the range obtained by CDF. For instance, for $m_t = 170$ GeV, $\alpha_s = 0.12$ and keeping hereafter the Higgs mass fixed at $m_H = 250$ GeV, for most observables the measured value is actually very close to the theoretical predictions, making the total χ^2 per degree of freedom reasonably low (< 2). However, there are a few exceptions for which recent data show some noticeable disagreement with respect to the SM expectations. A well-known case is the SLC measurement of the left–right polarized asymmetry A_{LR} [11] ($\chi^2 \sim 10$ for the above mentioned choice of input parameters). Some LEP results also show sizeable deviations. This is the case for the ratio of the Z width into b quarks to the total hadronic width, $R_b \equiv \Gamma_b/\Gamma_h$ ($\chi^2 \sim 4.5$), and for the τ forward–backward asymmetry A^{FB}_τ ($\chi^2 \sim 7$) [12]. (Clearly the actual value of the χ^2 function depends on the values adopted for the input parameters.)

For our analysis we have used the CC constraints on lepton universality and on CKM unitarity, the W mass measurement, as well as the NC constraints from the LEP and SLC measurements at the Z peak.

The best test of e–μ universality comes from $\pi \to e\nu$ compared to $\pi \to \mu\nu$. The ratio of the electron to the muon couplings to the W boson, extracted from the TRIUMF [13] and PSI [14] measurements, is $(g_e/g_\mu)^2 = 0.9966 \pm 0.0030$ [10].

Universality among the μ and τ leptons is tested by the τ leptonic decays compared to μ decay, giving $(g_\tau/g_\mu)^2 = 0.989 \pm 0.016$ [15]. A second test comes from $\tau \to \pi(K)\nu_\tau$, which gives $(g_\tau/g_\mu)^2 = 1.051 \pm 0.029$ [15]; this is almost 2σ off the SM, and hardly compatible with the above determination from τ decays. The use of this determination affects mainly our bounds for the mixing of the τ neutrino with new ordinary states, as discussed in Ref. [10].

For the test of the unitarity of the first row of the CKM matrix, we use the determination $\sum_{i=1}^{3} |V_{ui}|^2 = 0.9992 \pm 0.0014$ of Ref. [16], and for the W mass we take the average $M_W = 80.23 \pm 0.18$ [17] of the CDF and UA2 experimental values.

For the Z-peak data, we have included the measurements of the total Z width Γ_Z, the hadronic peak cross section σ_h^0, the ratios R_e, R_μ, R_τ of the total hadronic width to the flavour-dependent leptonic ones, the bottom and charm ratios R_b and R_c and forward–backward asymmetries A_b^{FB} and A_c^{FB}, and the leptonic unpolarized asymmetries A_e^{FB}, A_μ^{FB} and A_τ^{FB}. All the data up to 1993 as well as all the relevant experimental correlations given in Ref. [12] have been taken into account in our analysis. We also include in our set of constraints the measurements of the left–right polarization asymmetry at SLC, $A_{LR} = 0.1637 \pm 0.0075$ [11], and the measurement of the "theoretically equivalent" quantity $A_e^0 = \frac{2a_e v_e}{a_e^2 + v_e^2} = 0.120 \pm 0.012$ which has been inferred by the LEP collaborations from the angular distribution of the τ decay products [12]. These two different determinations of the same theoretical quantity are both more than 2σ off the SM value ($A_e^0 = 0.1419$ for our set of input parameters) and are in even more serious conflict between them, possibly indicating some problem in the analysis of the experimental data or an unlucky fluctuation.

We always use values for the observables that are extracted from the data without assuming universality, which is expected to be violated by the fermion mixings in the models we are considering. It is interesting to notice that, while the experimental leptonic partial width of the Z boson are in good agreement with the hypothesis of universality, some hint of a discrepancy may be present in the fitted flavour-dependent forward–backward asymmetries, which are $A_e^{FB} = 0.0158 \pm 0.0035$, $A_\mu^{FB} = 0.0144 \pm 0.0021$ and $A_\tau^{FB} = 0.0221 \pm 0.0027$ [12, 17].

Finally, we have also included in our data set the (updated) low-energy NC constraints (deep inelastic ν scattering and atomic parity violation). Although less effective than the Z peak data for constraining the kind of physics we are considering, they turn out to be relevant for our analysis in the case of the 'joint' fits to be discussed below.

6 Results

After constructing a χ^2 function with all the experimental measurements discussed in the previous section, we have derived bounds on the mixing parameters by means of the MINUIT package.

Regarding the gauge boson mixing ϕ, we give for the *unconstrained models* (e.g. with $M_{Z'}$ independent of ϕ) conservative bounds obtained letting the Z' mass to take values in the range $M_{Z'} > 500$ GeV and taking the extreme values $\phi_\pm$ that remain allowed at 90% c.l.. In this way we obtain

$$\begin{aligned} -0.0056 < \phi < 0.0055 \qquad &(\psi \text{ model}) \\ -0.0087 < \phi < 0.0075 \qquad &(\eta \text{ model}) \\ -0.0032 < \phi < 0.0031 \qquad &(\chi \text{ model}) \end{aligned} \tag{14}$$

These results have been obtained chosing for the input parameters the values $m_t = 170$ GeV, $m_H = 250$ GeV and $\alpha_s = 0.12$, which provide a good agreement between the experimental observables and the SM predictions (corresponding to vanishing Z-Z' and fermion mixings). Since the bounds on ϕ depend on the choice of input parameters, we show in Table 1 how the constraints are modified for $m_t = 150$ and 200 GeV and for $\alpha_s = 0.11$, 0.12 and 0.13[3]. It is apparent that the bounds become tighter for increasing m_t. This can be easily traced back to the fact that larger (absolute) values of ϕ and of m_t both tend to increase the value of the effective ρ parameter $\sim \rho_{mix} \cdot \rho_{top}$. For this reason the CDF lower limit on m_t is relevant for constraining ϕ. On the other hand, in the models considered here, increasing values of α_s lead to a shift towards negative ϕ values of the allowed region.

The previous bounds get also somewhat relaxed if one allows for the simultaneous presence of the fermion mixings, which can produce compensating effects. In this case, keeping from now on the same choice ($m_t = 170$ GeV, $m_H = 250$ GeV, $\alpha_s = 0.12$) for the input parameters, we get the 90% c.l. constraints

$$\begin{aligned} -0.0066 < \phi < 0.0071 \qquad &(\psi \text{ model}), \\ -0.0087 < \phi < 0.010 \qquad &(\eta \text{ model}), \\ -0.0032 < \phi < 0.0079 \qquad &(\chi \text{ model}). \end{aligned} \tag{15}$$

In contrast, tighter bounds result if one considers *constrained models*, that is assuming a relation between the gauge boson mixing and $M_{Z'}$ of the form $\phi \simeq C M_Z^2/M_{Z'}^2$, where C can be evaluated once the Higgs sector is specified. In this case the bounds on ϕ translate also into indirect constraints on $M_{Z'}$. The following results have been derived by assuming for each model a *minimal* Higgs content and the absence of singlet VEVs. For the ψ model, denoting by $\sigma \equiv (v_u/v_d)^2$ the square of the ratio of the scalar VEVs giving masses respectively to the u and d-type quarks, we have $C = -\frac{\sqrt{10}}{3} s_W \frac{\sigma-1}{\sigma+1}$. For $\sigma \to \infty$ we obtain $0 \geq \phi > -0.0042$, which implies the indirect constraint $M_{Z'} > 1.0$ TeV, while, for instance, for $\sigma = 2$ we obtain $0 \geq \phi > -0.0052$, corresponding to $M_{Z'} > 0.52$ TeV. For

[3] For a detailed discussion of the m_t (and m_H) dependence, see the last two references in [5].

Table 1: 90% c.l. lower (ϕ_-) and upper (ϕ_+) bounds on the the $Z - Z'$ mixing angle ϕ, in units of 10^{-2}, for the ψ, η and χ models. The limits correspond to different values of the top mass m_t and the strong coupling constant α_s, with the Higgs mass fixed to $m_H = 250$ GeV. They have been obtained by chosing the most conservative values as $M_{Z'}$ is allowed to vary from $\sim$ 500 GeV to infinity.

m_t [GeV]	α_s	E_6 model	ϕ_- [10^{-2}]	ϕ_+ [10^{-2}]
150	0.11	ψ	0	1.1
		η	0	1.3
		χ	0	0.75
	0.12	ψ	0	0.81
		η	0	1.0
		χ	-0.31	0.43
	0.13	ψ	-1.0	0
		η	-1.0	0
		χ	-0.70	0
200	0.11	ψ	-0.03	0.57
		η	-0.19	0.60
		χ	0	0.48
	0.12	ψ	-0.28	0.32
		η	-0.33	0.39
		χ	-0.18	0.25
	0.13	ψ	-0.43	0.11
		η	-0.38	0.23
		χ	-0.38	0.06

the η model ($C = \frac{4}{3} s_W \frac{\sigma - 1/4}{\sigma+1}$) the bound for $\sigma \to \infty$ is $0 \le \phi < 0.0035$, implying $M_{Z'} > 1.2$ TeV, while for $\sigma = 2$ we obtain $0 \le \phi < 0.0054$, implying $M_{Z'} > 0.76$ TeV. We recall that the Z_χ of the χ model is equivalent to the Z' present in $SO(10)$, being the two models different only with respect to the fermion and scalar representations. For the minimal Higgs content of $SO(10)$ ($C = s_W \sqrt{2/3}$ [18]) we obtain the constraint $0 \le \phi < 0.0028$, which implies $M_{Z'} > 1.2$ TeV for a Z' from $SO(10)$.

Turning now to the fermion mixings, we have listed in table 2 the updated 90% c.l. bounds obtained by allowing just one mixing to be present (single bounds) or allowing for the simultaneous presence of all types of fermion mixings (joint bounds). In the last case the constraints are generally relaxed due to possible accidental cancellations among different mixings. The bounds on the fermion mixings that can appear in E_6 models are given in the third column. In this case we have also allowed for the presence of mixing among the gauge bosons, which somewhat relaxes the limits. We present the results obtained in the χ model with the Z_0–Z_χ mixing as an additional free parameter.

The constraints we have listed in table 2 correspond to the particular value $\Lambda = 2$. However we stress that only the bound on $s_L^{\nu_\tau}$ depends significantly on the adopted value of Λ, since the ν_e and ν_μ mixings are mainly constrained by CC observables, which do not depend on this parameter. The LEP data alone already imply $(s_L^{\nu_\tau})^2 < 0.002/\Lambda_\tau$, which, due to the improvement in the determination of the invisible width, is significantly better than what obtained in previous analyses. For $\Lambda_\tau \simeq 0$ the constraint on $s_L^{\nu_\tau}$ arises from CC observables and can be found in ref. [10].

The results in table 2 were obtained for the reference values $m_t = 170$ GeV and $\alpha_s = 0.12$. Allowing m_t to vary in the range 150 to 200 GeV does not affect significantly the constraints on the fermion mixings. In contrast, increasing α_s up to $\alpha_s = 0.13$ worsens the limits on some of the hadronic mixings up to a factor ~ 2.

Besides strengthening the bounds on the new physics, one may also wonder whether it could be possible to account for some of the deviations with respect to the SM predictions that we have mentioned previously, by means of the new physics effects that we have been discussing here. Regarding the $\sim 2\sigma$ excess reported in the measurement of R_b, the observed deviation ($\Gamma_b^{exp} > \Gamma_b^{SM}$) has the opposite sign than the one resulting from a mixing of the bottom quark with exotic states. In fact, since $\Gamma_b \propto v_b^2 + a_b^2$, at $O(s_{L,R}^2)$ we have

$$\frac{\Gamma_b}{\Gamma_b^{SM}} \simeq 1 + (s_L^b)^2 \frac{v_0^b + a_0^b}{(v_0^b)^2 + (a_0^b)^2} + (s_R^b)^2 \frac{a_0^b - v_0^b}{(v_0^b)^2 + (a_0^b)^2} \simeq 1 - 2.2 (s_L^b)^2 - 0.2 (s_R^b)^2. \qquad (16)$$

Hence, non-vanishing values for both s_R^b and s_L^b have the effects of reducing Γ_b, thus increasing the disagreement with the measurements. Of course this behaviour is in part responsible for the drastic improvement in the constraints on the b mixing angles. In addition, due to the effect of the top mass on the Zbb vertex corrections, the constraint arising from R_b slightly improves with larger m_t (the measured R_b favours a lower m_t value).

In the case of the different leptonic asymmetries, the LEP experimental values are not in complete agreement with the assumption of universality, since A_τ^{FB} is somewhat larger than $A_{e,\mu}^{FB}$. The very small SM value of the charged lepton vector coupling $v_0^l \simeq -0.036$ implies that $A_l^0 \simeq v^l/a^l$ is very sensitive to tiny effects of new physics affecting v^l, as for

Table 2: The 90% c.l. upper bound on the ordinary–exotic fermion mixing parameters. The 'single' limits in the first column are obtained when the remaining mixing parameters are set to zero. For the 'joint' bounds in the second column, cancellations among the effects of all the different possible fermion mixings are allowed. The third column gives the 'joint' bound in the χ model, taking into account the possible cancellations among the effects of all the ordinary–exotic mixing parameters present in E_6 as well as of a $Z_0 - Z_\chi$ mixing. All the results presented correspond to the value $\Lambda = 2$ of the parameter describing the type of new neutrinos involved in the mixing, with the fixed values $m_t = 170$ GeV, $m_H = 250$ GeV and $\alpha_s = 0.12$.

	Single limit	Joint limit	χ model
$(s_L^e)^2$	0.0018	0.0065	
$(s_R^e)^2$	0.0020	0.0020	0.0024
$(s_L^\mu)^2$	0.0017	0.0076	
$(s_R^\mu)^2$	0.0034	0.0059	0.0045
$(s_L^\tau)^2$	0.0016	0.0058	
$(s_R^\tau)^2$	0.0030	0.0055	0.0037
$(s_L^u)^2$	0.0024	0.012	
$(s_R^u)^2$	0.0090	0.015	
$(s_L^d)^2$	0.0023	0.013	0.0064
$(s_R^d)^2$	0.019	0.029	
$(s_L^s)^2$	0.0036	0.0087	0.019
$(s_R^s)^2$	0.021	0.060	
$(s_L^c)^2$	0.0042	0.019	
$(s_R^c)^2$	0.010	0.17	
$(s_L^b)^2$	0.0020	0.0025	0.0045
$(s_R^b)^2$	0.010	0.015	
$(s_L^{\nu_e})^2$	0.0050	0.0066	0.0064
$(s_L^{\nu_\mu})^2$	0.0018	0.0060	0.0046
$(s_L^{\nu_\tau})^2$	0.0096	0.018	0.017

example the shift $\delta v^l = [(s_L^l)^2 - (s_R^l)^2]/2$ induced by a mixing of the leptons. An increase in A_τ^{FB} could then result from a non-zero s_R^τ. However, since this fermion mixing would modify simultaneously the axial coupling a^τ by a similar amount, it is easy to check that the constraints from Γ_τ do not allow the 50% increase required to explain the measured A_τ^{FB} (in the presence of s_R^τ, $\delta A_\tau/A_\tau \simeq -2\delta\Gamma_\tau/\Gamma_\tau$). New physics effects could be able to account for these deviations only if they affect mainly the τ vector coupling, while leaving the axial-vector coupling close to its SM value. Regarding the measurement of A_{LR}^{SLC}, even if one were to ignore the discrepancy with the LEP measurement of A_e^0, the same type of argument would prevent the possibility of explaining the measured value by means of a mixing of the electron.

Clearly the deviations in Γ_b and A_τ^{FB} cannot be explained either by introducing a Z' boson of the type we have considered here, since these new gauge interactions are universal and would affect all generations. However, some models involving a new gauge boson coupling mainly to the third generation have been discussed in this context [19].

In conclusion, LEP provides a powerful tool for the indirect search of several types of physics beyond the SM. Present observations do not hint to any of the new physics effects that have been discussed here, thus allowing for a significant improvement of the limits on the indirect effects induced by some of the new particles that appear in many extensions of the SM.

References

[1] P. Langacker and D. London, Phys. Rev. **D38** (1988) 886.

[2] E. Nardi, E. Roulet and D. Tommasini, Nucl. Phys. **B386** (1992) 239.

[3] E. Nardi and E. Roulet, Phys. Lett. **B248** (1990) 139;
G. Bhattacharyya et al., Phys. Rev. Lett. **64** (1990) 2870;
G. Bhattacharyya et al., Mod. Phys. Lett. **A6** (1991) 2921;
C.P. Burgess et al., Phys. Rev. **D49** (1994) 6115;
G. Bhattacharyya, Phys. Lett. **B331** (1994) 143.

[4] E. Nardi, E. Roulet and D. Tommasini, Phys. Rev. **D46** (1992) 3040.

[5] P. Langacker and M. Luo, Phys. Rev. **D45** (1992) 278;
P. Langacker, M. Luo and A.K. Mann, Rev. Mod. Phys. 64 (1992) 87;
J. Layssac, F.M. Renard and C. Verzegnassi, Z. Phys. **C53** (1992) 97;
M.C. Gonzalez García and J.W.F. Valle; Phys. Lett. **B259** (1991) 365;
G. Bhattacharyya et al., Mod. Phys. Lett. **A6** (1991) 2557;
O. Adriani et al.Phys. Lett. **B306** (1993) 187;
G. Altarelli et al., Phys. Lett. **B263** (1991) 459;
G. Altarelli et al., Phys. Lett. **B318** (1993) 139;
F. del Aguila et al., Nucl. Phys. **B372** (1992) 3.

[6] CDF Collaboration, F. Abe et al., Phys. Rev. Lett. **73** (1994) 225.

[7] D. Bardin et al., preprint CERN-TH 6443/92.

[8] For a review on Z' constraints, see F. del Aguila, M. Cvetič and P. Langacker, *Proceedings of the 2nd International Workshop on Physics and Experiments at Linear e^+e^- Colliders*, Waikoloa, Hawaii, 1993, F. Harris et al.eds. (World Scientific, Singapore, 1993) Vol. II, p. 490.

[9] D. London, in *Precision Tests of the Standard Model*, ed. P. Langacker (World Scientific, 1993); E. Nardi, in Ref. [8], Vol. II, p. 496; C.P. Burgess et al., [3].

[10] E. Nardi, E. Roulet and D. Tommasini, Phys. Lett. **B327** (1994) 319.

[11] SLD Collaboration, K. Abe et al., Phys. Rev. Lett. **73** (1994) 25.

[12] The LEP Electroweak Working Group, DELPHI 94-33 PHYS 364 (1994).

[13] D.I. Britton et al., Phys. Rev. Lett. **68** (1992) 3000.

[14] G. Czapek et al., Phys. Rev. Lett. **70** (1992) 17.

[15] J.M. Roney, in *Proc. of the Second Workshop on Tau Lepton Physics*, ed. K.K. Gan (World Scientific, Singapore, 1993).

[16] A. Sirlin, in *Precision Test of the Standard Electroweak Model* ed. P. Langacker (World Scientific, Singapore, 1993).

[17] B. Pietrzyk, Annecy preprint LAPP-EXP-94.07 (1994).

[18] See for example P. Langacker and M. Luo, in Ref. [5].

[19] B. Holdom, University of Toronto preprint UTPT-94-20 (1994).